

FUTURE POSSIBILITIES FOR DETECTING HI AT HIGH RED-SHIFT

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To appear in: "Cold Gas at High Redshift"
Eds. M.Bremer et al. (Kluwer, Dordrecht)

1. Introduction

The 21-cm line of neutral hydrogen is in many respects the most valuable tracer of neutral gaseous mass in astrophysics. Even though neutral gas becomes predominantly molecular at high densities, the 21-cm line emission of the associated atomic component allows the total gaseous mass of (proto) galactic concentrations to be estimated to about a factor of two, even in the most extreme cases observed to date. This is in marked contrast to, for example, the luminosity of carbon monoxide emission lines originating in the molecular component. For the same total gaseous mass, these emission lines are observed to vary in luminosity over a factor of about 10^4 depending on the abundance of heavy elements and the intensity of illumination to which they are subjected.

It is also important to draw the distinction between the sensitivity to the neutral gaseous mass of distinct concentrations with the sensitivity to column density along discrete lines-of-sight. The extremely large absorption cross-section of neutral hydrogen to Lyman- α radiation guarantees a correspondingly high sensitivity to neutral hydrogen columns along lines-of-sight to suitable background sources of (red-shifted) ultra-violet light. However, the paucity and compact nature of such background probes implies that gas masses can never be determined for individual objects via such observations of absorption. An emission line tracer of the neutral gas remains essential for this purpose.

In this paper we will briefly review the beginnings of HI astronomy, proceed to an assessment of our current capabilities in this area, and continue by considering what will be necessary to push back the frontier to cosmological distances. We will then consider how such a leap in performance might be realized.

2. Where have we come from?

After the prediction of the existence of the HI 21-cm line by Van de Hulst (1945) it was only a few years before several independent groups detected the line emission from our Galaxy and reported it simultaneously in a 1951 issue of *Nature* (Ewen and Purcell, Muller and Oort). Even in the preliminary discovery report, important contributions were made by Muller and Oort (1951) to our knowledge of the kinematics and morphology of the gaseous disk of our Galaxy. This was followed, in short order, with major surveys of spiral structure and kinematics of the Galaxy (Van de Hulst, Muller and Oort, 1954)

3. Where are we now?

The years since 1951 have seen a major improvement in our abilities to observe HI in galaxies. An illustration of this improvement is given in Figure 1 where the continuum sensitivity is plotted after one minute of integration for many radio telescopes as they became available. Since upgraded receiver systems have often been added to existing facilities after construction, these are also indicated in the figure in a number of cases. An exponential improvement in sensitivity over at least 6 orders of magnitude is apparent between about 1940 and 1980. Instruments like the WSRT and the VLA have become available on a schedule which maintained a high rate of discovery. The Arecibo telescope stands out as a major leap in sensitivity performance at a relatively early date.

Figure 1. The time evolution of radio telescope sensitivity. The continuum sensitivity after one minute of integration is indicated for a number of radio telescopes as they became available. Solid lines indicate up-grade paths of particular instruments.

Sensitivity within the narrow bandwidth of a spectral line observation has evolved in a very similar way to that illustrated in Figure 1. We have now progressed to the point where we can study the neutral gas content, distribution and kinematics within individual galaxies at recession velocities as high as about $24,000 \text{ km s}^{-1}$. This is perhaps best illustrated by a recent deep integration (about 100 hours) with the VLA obtained by Van Gorkom (1995) to image HI in galaxies of the cD cluster A2670. Some 20 cluster galaxies are detected within an area of about 0.25 square degrees with an rms sensitivity of $80 \mu\text{Jy beam}^{-1}$ per 48 km s^{-1} channel. The corresponding 5σ detection limit for a galaxy spanning 100 km s^{-1} is about $4 \times 10^8 h^{-2} M_{\odot}$.

As impressive as this result is, it also underlines the sad fact that current instrumentation only allows us to determine neutral gas masses for galaxian concentrations out to a red-shift of about 0.1. Given all the evidence for

substantial evolution of the gas mass at red-shifts between perhaps 0.2 and 0.5, let alone the dramatic evolution expected between $z = 0.5$ and 2, this is particularly frustrating.

4. Where are we headed?

An overview of how current and upcoming instrumentation measures up to the problem of detecting HI emission from distant systems is given in Figure 2. The continuum and line emission of the luminous spiral galaxy M101 has simply been re-scaled to simulate its appearance at the indicated red-shifts of 0.12, 0.25, 0.5, 1, 2 and 4. For this illustration, no time evolution of the emission spectrum has been assumed, even though it is clear that the large stellar mass which is now present was once also in the form of gas. The rms sensitivities of a variety of existing and planned instruments (assuming a spectral resolution of 10^4 and an integration time of 12 hours) have been overlaid on these spectra. The HI emission line of such a gas-rich system ($M_{HI} = 2 \times 10^{10} M_{\odot}$) is easily detectable by the VLA and WSRT near $z = 0.1$, but will probably demand the GMRT for detection at $z = 0.3$.

Figure 2. Red-shifted unevolved spectra of M101 compared to the spectral line sensitivity of current and planned facilities at frequencies between 10^8 and 10^{12} Hz. The solid lines are the composite emission spectra red-shifted to $z = 0.12, 0.25, 0.5, 1, 2$ and 4. Note that the continuum and spectral line features of the composite spectra are sampled with different effective bandwidths. Telescope names are placed at the rms sensitivity level after one “transit” of integration at a spectral resolution of 10^4 .

An important point to note is that it is not merely a question of having enough sensitivity to detect the HI emission line, but also that the appropriate frequency coverage be available. For example, the VLA 20-cm band extends from 1320–1700 MHz at 0.9 times nominal sensitivity, reaching only to $z = 0.08$ in HI. The highest frequency band of the GMRT on the other hand is expected to extend from 1000–1420 MHz, so that red-shifts as high as 0.4 may become accessible.

Finally, it is essential that the frequency in question is not rendered unusable by radio frequency interference. This is in fact the reason that only synthesis arrays have been plotted in Figure 2. Experience has shown that total power instruments, like Arecibo and the Green Bank 140 foot telescope are unable to achieve noise limited performance in those portions of the spectrum which are in active use. For several reasons, synthesis arrays are much less vulnerable to external interference. This is an issue to which we will return below.

Another way of illustrating upcoming performance is given in Figure 3. In this case the performance of the upgraded WSRT (as expected in 1997)

is illustrated for a long integration of 400 hr duration. The limiting HI mass is plotted as function of red-shift for both the case of “detection” and “imaging”. “Detection” is defined here as requiring a 5σ signal in a single 50 km s^{-1} velocity channel, while “imaging” is defined as requiring a 5σ signal in each of six independent velocity channels of 50 km s^{-1} width. The solid curves, which extend from $z = 0\text{--}0.2$ and $z = 2.6\text{--}4.7$, indicate the frequency ranges where optimized receiver systems will be available. Almost continuous coverage of the remaining interval, $z = 0.2\text{--}2.6$, will also be available for the first time with the new receiver system, although at a reduced sensitivity.

Figure 3. Current and future capabilities for detecting and imaging HI as a function of red-shift for an integration of 400 hour duration. “Detection” is defined to imply a 5σ signal in a single 50 km s^{-1} channel, while “Imaging” implies a 5σ signal in each of 6 independent channels of 50 km s^{-1} width.

The preceding discussion has illustrated how inadequate the current generation of instruments will be to study galaxian gas masses out to cosmological distances. This fact has been one of the major drivers for pursuing a next generation facility with about two orders of magnitude greater sensitivity than what is now available. Since the requirement is basically for about 10^6 m^2 of collecting area, the proposed facility has come to be called the “Square Kilometer Array Interferometer”.

The astute reader will already have noted that the capabilities of such a new instrument have been overlaid on Figures 1, 2 and 3. From Figure 1 it is clear that the SKAI sensitivity is what is required to maintain the exponential improvement in performance that accompanied the decades of broad ranging discovery between 1950 and 1990. Returning specifically to the detection of the HI emission line, Figure 2 illustrates how individual galaxies, like M101, would be within the reach of such an instrument out to red-shifts greater than 2. This capability is placed in a more continuous context in Figure 3, where it can be seen that SKAI will effectively open much of the universe to direct study of (sub-)galaxian neutral gaseous masses and how they have evolved.

While sufficient sensitivity to detect the integrated signal from gaseous concentrations tells part of the story, another important concern is having sufficient spatial resolution to allow kinematic and morphological studies to be undertaken. The combined imaging and detection capabilities of SKAI are illustrated in Figure 4, assuming that most of the instrumental collecting area is concentrated in a circular region of about 50 km in diameter. The angular resolution in the red-shifted HI line then varies between about an arcsec locally to 2 arcsec by $z = 1$. This combination of collecting area

and array size has been chosen to provide about 1 Kelvin of brightness sensitivity for spectral imaging applications within a 24 hour integration. An actual HI data-cube of M101 has been resampled and rescaled to simulate its appearance at the indicated red-shifts of 0.2, 0.45 and 0.9. The peak observed brightnesses are shown in the left hand panels, while the derived velocity fields are shown on the right. From the figure it is clear that fairly detailed kinematic studies (including kinematic detection of spiral arms, rotation curves, etc.) of “normal” systems will be possible to at least $z = 0.5$, while crude kinematics (basic orientation and rotation parameters) will be possible to $z = 1$ or more. In addition, it should be borne in mind that the actual field-of-view and spectral bandpass of a SKAI observation will be many times that shown in Figure 4. While each panel of the figure is only 230 kpc on a side, the likely SKAI field-of-view will correspond to about 1.5, 3 and 5 Mpc at the three red-shifts shown. At the same time a total observing bandwidth of 100–200 MHz will probe a cylindrical volume about 200 Mpc deep. Each pointed observation will therefore provide serendipitous kinematic data on several hundred field galaxies.

Figure 4. Simulated SKAI observations of M101 as it would appear at red-shifts of 0.2, 0.45 and 0.9. Peak observed brightnesses are shown in the left hand panels and corresponding velocity fields on the right. The assumed integration time is indicated above each panel.

So far we have assumed that the gas properties of galaxies at earlier epochs are similar to those of current galaxies in making some predictions of what might be achieved. It would be very surprising if the universe were to behave in such a boring fashion. At the current epoch, the vast majority of the gas that is gravitationally bound by individual galaxies has already been cycled through, and to a great extent locked in the form of, stars. If we can reach back to the time when much of the early activity was taking place, which may correspond to the quasar epoch between $z = 2$ –3, the current proportions may well be reversed.

A better indication of what we might expect to find in the early universe is beginning to emerge from extensive numerical simulations of structure and galaxy formation (eg. Weinberg 1995, Ingram 1995). In Figures 5, 6 and 7 we have taken the simulated neutral hydrogen densities predicted by these simulations at red-shifts of 2, 3 and 4 (CDM with $\Omega = 1$, $\Omega_B = 0.05$, $H_0 = 50 \text{ km s}^{-1}$, $\sigma_{16} = 0.7$) in a co-moving volume that is $22.22/(1+z)$ Mpc on a side and overlaid the five sigma detection contour of SKAI after a long integration time of 1600 hr. Within a single pointing of the SKAI, and each 2.5 MHz of spectral bandwidth we might expect a handful of detections at $z = 4$, perhaps 50 at $z = 3$ and some hundreds at $z = 2$. Rather than being carried out as separate experiments, the instrumental

bandwidth and spectral resolution are likely to be sufficient to observe the entire red-shift interval 2–4 simultaneously. Based on the detection frequencies noted above, we would then expect such a single experiment to allow study of some 8000 high red-shift systems.

Figure 5. Simulated HI emission at $z = 2$ with SKAI detections overlaid. The linear grey-scale indicates the predicted peak brightness of HI emission in a $22.2/(1+z)$ Mpc cube and extends from $\log(M_{\odot}/\text{Beam}) = 1.7 - 10.8$. The single white contour at $\log(M_{\odot}/\text{Beam}) = 9.22$ is the 5σ SKAI detection level after a 1600 hour integration.

Figure 6. Simulated HI emission at $z = 3$ with SKAI detections overlaid. The linear grey-scale indicates the predicted peak brightness of HI emission in a $22.2/(1+z)$ Mpc cube and extends from $\log(M_{\odot}/\text{Beam}) = 2.6 - 10.7$. The single white contour at $\log(M_{\odot}/\text{Beam}) = 9.72$ is the 5σ SKAI detection level after a 1600 hour integration.

Figure 7. Simulated HI emission at $z = 4$ with SKAI detections overlaid. The linear grey-scale indicates the predicted peak brightness of HI emission in a $22.2/(1+z)$ Mpc cube and extends from $\log(M_{\odot}/\text{Beam}) = 3.4 - 10.7$. The single white contour at $\log(M_{\odot}/\text{Beam}) = 10.13$ is the 5σ SKAI detection level after a 1600 hour integration.

Of course the actual number and distribution of detections at these red-shifts will probably be quite different than illustrated in Figs. 5-7. However, those differences are likely to make it possible to determine the cosmological model that actually applies to our universe.

5. How will we get there?

Some of the basic instrumental parameters of the SKAI have already emerged from the previous discussion. The highest possible sensitivity (corresponding to a baseline geometric collecting area of 10^6 m^2) is required over frequencies from about 200–1400 MHz. This should be coupled with the highest angular resolution that retains sufficient brightness sensitivity for HI emission line detection. In practise this implies an array distributed over a region of 30–50 km diameter. The instantaneous field-of-view should be as large as possible (from scientific considerations) while not limiting system performance on long integrations at these relatively low frequencies. Considering both ionospheric non-isoplanicity as well as sky model complexity suggests a unit telescope size of between 100 and 300 meter diameter. Instantaneous synthesized image quality must be sufficient to allow adequate modeling of a time variable sky model (including ground and space-based interfering sources), leading to a minimum requirement of about 32 well-distributed units which would be cross-correlated.

The above requirements are embodied in the schematic configuration shown in Figure 8. A densely packed elliptical zone accounts for some 80% of the array collecting area. The remaining 20% of the collecting area is distributed over a much larger region to permit sub-arcsec resolution to be employed for other applications like imaging in continuum radiation and HI absorption.

Figure 8. Schematic configuration of SKAI. Note that the unit telescopes are not depicted to scale.

Although the basic parameters of the instrument and its schematic configuration can be derived in a straight forward manner, the method of realizing such an enormous collecting area at an affordable price is less clear. Looking back at Figure 1, there are indications that some leveling out of sensitivity with time has already set in since about 1980. This is almost certainly the result of having reached limits in the performance to cost ratio of traditional radio telescope technologies. We have now reached the point where system performance is no longer limited by receiver noise, but primarily by the raw collecting area itself. Traditional technologies have not yet made great progress in reducing the cost of raw collecting area by orders of magnitude. The most cost effective designs from this point of view have been the Arecibo fixed spherical reflector and the GMRT low mass paraboloid. How might we proceed to even greater cost-effectiveness for the unit telescopes?

Several possible element concepts for the SKAI are illustrated in Figure 9. At the heart of each of these concepts is a much greater reliance than ever before on mass produced and highly integrated receiver systems together with much more extensive digital electronics for beam formation. In the top panel we depict one conceivable extreme in a continuous range of possibilities. In this case the wavefront is detected by individual active elements comparable to a wavelength in size. Each of these is amplified, digitized and combined with the others to form an electronically scan-able beam (or beams) with no moving parts whatsoever. The challenge in this case lies in achieving extremely low component and data distribution costs since literally millions of active elements will be required. In the center panel, some degree of field concentration is first achieved with the use of small paraboloids before amplification, digitization and beam formation. In this case, active element number is reduced to some thousands and greater sky coverage at high sensitivity is also realized, although at the expense of the mechanical complexity of the paraboloid drive and tracking system. In the lower panel we depict the other conceptual extreme, whereby a single large reflector is used for each of the unit telescopes. Extensive arrays of

active elements would be employed in this concept to intercept the focal region of the spherical primary in order to efficiently illuminate the surface and allow multiple beams to be formed.

Figure 9. Possible element concepts for the SKAI.

The adaptive beam formation technology which underlies all of the element concepts just considered is extremely attractive for a number of reasons. Real-time beam formation with at least thousands if not millions of active elements provides a comparable number of degrees of freedom for tailoring the beam in a desired way. The basic properties of high gain in some direction and low side-lobe levels elsewhere are fairly obvious and traditional requirements. An additional possibility, which hasn't yet been applied in radio astronomy, is that of placing response *minima* in other desired directions, such as those of interfering sources. In addition, the way is naturally opened to exploit multiple observing beams on the sky to enhance the astronomical power of the instrument many-fold. These might be used to provide simultaneous instrumental calibration, support multiple, fully independent observing programs or enlarge the instantaneous field-of-view for wide-field applications. Finally, the great potential of adaptive beam formation has led to a strong commercial interest in this technology. This has opened the way to collaborative R&D efforts which are now beginning to take shape.

During the interval 1995–2000, a concerted effort at R&D for SKAI will be undertaken both within the NFRA and at collaborating institutes. The various concepts depicted in Figure 9 (and potentially new ones) will be worked out in sufficient detail to allow realistic cost estimates to be made. Proto-typing of cost effective technologies as an extension to the WSRT array is planned for the period 2001–2005. Assuming the successful completion of both technical preparations and funding arrangements, construction of the instrument is envisioned for the period 2005–2010.

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